

Structural brain changes with second language learning: A longitudinal voxel-based morphometry study

Cong Liu^{a,b}, Lu Jiao^a, Kalinka Timmer^c, Ruiming Wang^{b,*}

^a Department of Psychology, Normal College & School of Teacher Education, Qingdao University, Qingdao, China

^b Key Laboratory of Brain, Cognition and Education Sciences, Ministry of Education, & Guangdong Provincial Key Laboratory of Mental Health and Cognitive Science, Center for Studies of Psychological Application, School of Psychology, South China Normal University, Guangzhou, China

^c Psychology of Language and Bilingualism Lab, Institute of Psychology, Jagiellonian University, Kraków, Poland

ARTICLE INFO

Keywords:

Second language learning
Language control
Voxel-based morphometry
Structural MRI

ABSTRACT

The underlying mechanisms that adapt with L2 learning are still poorly understood. The present longitudinal study examined the effects of L2 learning on grey matter structure of Chinese college freshmen majoring in English. Participants were scanned twice, one year apart. Our voxel-based morphometry analyses revealed that gray matter volume (GMV) decreased in the left anterior cingulate cortex (ACC) and right inferior frontal gyrus (IFG) after L2 learning for one year. Critically, these structural adaptations correlated with changes in participants' language control ability across L2 learning. Moreover, age of acquisition of L2 was a significant predictor of volumetric change in the left ACC and L2 proficiency was a significant predictor of volumetric change in the right IFG. Overall, these findings enrich our understanding of the dynamic nature of structural brain adaptations, and the mechanisms these adaptations index, as a function of classroom L2 learning.

1. Introduction

Various real-life experiences have been related to structural brain modulations (Bialystok, 2017; Draganski & May, 2008; Draganski et al., 2004; Ilg et al., 2008; Krafnick, Flowers, Napoliello, & Eden, 2011; Kraus & White-Schwoch, 2017; Maguire et al., 2000) and the last two decades revealed that learning a second language (L2) is another life experience that induces structural adaptations (see for review Li, Legault, & Litcofsky, 2014; Pliatsikas, DeLuca, & Voits, 2020; but see Danylykiv & Krafnick, 2020 for the absence of anatomical modulations). However, little is known about how longitudinal L2 learning in a naturalistic setting exerts an influence on brain structure. Variations in different dimensions of the multilingual experience, like L2 proficiency and Age of Acquisition (AOA), are crucial individual experience-based factors that help advance our understanding of the bilingual brain. Hence, the present study adopted a longitudinal structural magnetic resonance imaging (sMRI) approach to investigate how the structural brain adapts to long-term L2 classroom learning over the course of one year while paying specific attention to individual differences in L2 learning experience that could modulate structural brain adaptations.

1.1. Structural brain adaptations to L2 learning experiences

In recent years, a growing body of evidence from both cross-sectional (Del Maschio, Fedeli, Sulpizio, & Abutalebi, 2019; Luo et al., 2019; Pliatsikas, DeLuca, Moschopoulou, & Saddy, 2017; Yamasaki, Stocco, Liu, & Prat, 2019; Zou, Ding, Abutalebi, Shu, & Peng, 2012) and longitudinal studies (Legault, Fang, Lan, & Li, 2019; Mårtensson et al., 2012) has suggested that both acquiring an L2 and longer-term bilingualism impacts, among others, the grey matter structure of the brain (for reviews, see Li et al., 2014; Pliatsikas et al., 2020). However, the findings of these studies seem inconsistent in terms of directionality and location of the structural grey matter changes. Specifically, while most studies reported an increase in grey matter volume (GMV) (for a review, see Li et al., 2014) in specific structure of the brain for bilinguals as compared to monolinguals, only a few studies reported a decrease in GMV (e.g., Klein, Mok, Chen, & Watkins, 2014). The two most recent models that describe adaptations due to bilingual experience (i.e., BAPPS: bilingual anterior to posterior and subcortical shift model, Grundy, Anderson, & Bialystok, 2017; DRM: dynamic restructuring model, Pliatsikas, 2020) suggest that structural brain adaptations are dynamic and can be expressed as cycles of local tissue increases and decreases depending on the duration of L2 learning. However, there is a

* Corresponding author at: School of Psychology, South China Normal University, 510631 Guangzhou, China.

E-mail address: wangrm@scnu.edu.cn (R. Wang).

<https://doi.org/10.1016/j.bandl.2021.105015>

Received 28 February 2021; Received in revised form 24 August 2021; Accepted 26 August 2021

Available online 11 September 2021

0093-934X/© 2021 Elsevier Inc. All rights reserved.

lack of empirical evidence directly supporting this argument. In the present study, we will empirically investigate how structural grey matter adapts to classroom L2 learning across one year.

The BAPSS model proposes that with prolonged L2 learning, there is a decreased reliance on frontal cortical regions, such as the anterior cingulate cortex (ACC) and the inferior frontal gyrus (IFG), due to more efficient and automated language control processing. This co-occurs with a shift to relying more on subcortical regions (e.g., left Caudate) and posterior regions (e.g., occipital lobes) responsible for perceptual/motor functions. Following the BAPSS model, Pliatsikas (2020) further proposed three stages of structural adaptations to L2 learning in their DRM model: the initial exposure stage, the consolidation stage, and the peak efficiency stage. During the *initial exposure* stage of L2 learning, increased control demands lead to an increased reliance on cortical regions (e.g., ACC and IFG) implicated in language control. Then, with prolonged L2 learning, the language control process becomes more efficient during the *consolidation* stage. This stage is accompanied by increases in subcortical regions (e.g., LCN, thalamus) and the initially observed restructuring in the cortical regions during the initial exposure stage reverting to the baseline levels. During the final *peak efficiency* stage, efficient and automatic language control is expected to lead the observed subcortical changes in the previous stage (i.e., consolidation stage) to disappear slowly, with a shift to a greater reliance on posterior regions. Both theoretical frameworks suggested that the adaptations to L2 learning are continuous and dynamic. Longitudinal studies can empirically investigate how L2 learning shapes the structural brain in contrast with cross-sectional studies, which cannot provide the complete picture of dynamicity.

We propose that one critical mechanism underlying brain adaptation to L2 learning could result from the changes in the mechanism that handles choosing the intended language while avoiding the unintended language (i.e., bilingual language control; for a review, see Bobb & Wodniecka, 2013). Specifically, it has been shown that both languages are jointly activated and compete for selection in the bilingual mind (Dijkstra & van Heuven, 2002; Green, 1998; Jiao, Liu, Schwieter, & Chen, 2021). When bilinguals aim to speak in one language (i.e., target language), they must employ their language control ability to minimize cross-language interference from another language (i.e., non-target language). With prolonged and intensive experience of handling two languages during L2 learning, language control in bilinguals is suggested to become more efficient and automated (for a review, see DeLuca, Segaert, Mazaheri, & Krott, 2020). As L2 learning engages an extensive network of the brain and is cognitively stimulating, changes in domain-general attentional control have also been reported (Bak, Long, Vega-Mendoza, Sorace, & Allen, 2016). Thus, with increased L2 exposure, adaptations throughout brain regions associated with bilingual language control are expected.

Two recent longitudinal studies have hinted that L2 learning and bilingual experiences induce structural adaptations in some brain regions associated with language control (DeLuca, Rothman, & Pliatsikas, 2019; Legault et al., 2019). However, these studies did not employ a behavioral task to assess language control (e.g., language-switching task), and therefore, we cannot be sure the changes in the brain are directly related to increased bilingual control efficiency. Thus, as neuroimaging data are difficult to be interpreted without behavioral data (García-Pentón, Fernández García, Costello, Duñabeitia, & Carreiras, 2016; Paap, Johnson, & Sawi, 2015), it remains unclear how brain adaptations due to L2 learning are correlated with changes in the efficiency of bilingual language control. We propose that bilingual language control is one of the potentially crucial mechanisms underlying brain adaptation during L2 learning.

1.2. The relationship between individual differences in L2 learning experience and structural brain adaptations

Given the complexity and diversity in L2 learning and bilingual

experience, recent research has recommended that bilingualism should be treated as a continuum instead of a monolithic variable (DeLuca, 2019; Fedeli, Del Maschio, Sulpizio, Rothman, & Abutalebi, 2021; Pliatsikas, DeLuca, & Voits, 2020). Specifically, De Bruin (2019) indicated that bilinguals differ from each other in various ways, such as their language proficiency and L2 age of acquisition (AoA) (De Bruin, 2019). However, previous studies typically compared bilinguals to monolinguals with no account of individual differences, which led to variability in the available findings. Pliatsikas (2020) proposed to overcome this by among others viewing bilingualism as a dynamic continuum. In this line, an increasing number of studies have focused on examining how individual experiences of bilinguals modulate brain adaptations. For example, differences between participants in L2 AoA revealed adaptations in the volume and shape of the caudate (Hervais-Adelman, Egorova, & Golestani, 2018), in the fractional anisotropy in the corpus callosum (Luk et al., 2020), and in the cortical thickness in the left IFG and negatively in the right IFG (Klein et al., 2014). L2 language proficiency is also correlated with the caudate (Hervais-Adelman et al., 2018) and gyrfication in the right posterior cingulate cortex (Del Maschio et al., 2018). These findings help determine which experience-based factors of L2 performance can explain variability in brain adaptation due to L2 learning.

However, only a few studies correlated individual experiences to structural adaptations in the bilingual brain with a longitudinal design. DeLuca et al. (2019) revealed structural adaptations in the cerebellum due to L2 AoA and length of L2 immersion over the course of approximately three years. Legault et al. (2019) showed greater GMV in the right IFG with earlier L2 AoA during two semesters (i.e., about four months) of L2 Spanish classroom learning for native English speakers. Taking both longitudinal studies together provides evidence for BAPSS and DRM (i.e., cortical expansions with early L2 exposure and posterior/subcortical adaptation with prolonged exposure). Furthermore, the findings from both studies help determine which experience-based factors of L2 performance can explain variability in brain adaptation due to L2 learning. Thus, the first findings suggest a crucial role for two main dimensions defining bilinguals' individual experiences (i.e., L2 AoA and L2 proficiency). However, it remains unclear how these bilinguals' individual experiences may be associated with brain adaptation due to longer-term classroom L2 learning for Chinese freshmen, who may be at a different stage of L2 learning than the previously discussed longitudinal studies.

1.3. The present study

The present study aimed to investigate the effect of classroom L2 learning in a naturalistic setting across one year on grey matter structure. A group of Chinese college freshmen majoring in English were scanned approximately one year apart. During this period, the freshmen took various English courses in an immersive classroom setting. L2 learning was more naturalistic as compared to traditional L2 learning in a laboratory setting. We focused on potential changes in gray matter structure associated with language control that are crucial in naturalistic classroom settings and in real-life. We also examined how individual differences in L2 AoA and L2 proficiency may be associated with any potential changes across one year of L2 learning.

Given that the participants recruited in the present study were Chinese students with English as important compulsory courses throughout junior high school, we believe the participants fit into the consolidator phase, as described in the DRM, during the first scanning session. We believe participants moved to peak efficiency at the second scanning session due to one-year intensive L2 learning in an immersive English classroom setting with 6–8 h of immerse classroom practice every weekday. Hence, we predicted that cortical GMV in frontal regions, related to language control (including ACC and IFG), will decrease after one year of L2 learning. In contrast, the GMV in subcortical structure and posterior regions related to perceptual/motor functions may increase

after one year of L2 learning. We also predicted that these GMV changes will vary as a function of individual differences in language control performance, which would help uncover the potential mechanism underlying structural adaptations to L2 learning. Furthermore, we assessed whether individual differences in L2 learning experience modulated the structural changes, aiming to provide additional insights in L2 learning-dependent structural brain adaptations.

2. Method

2.1. Participants

The present study recruited 25 Chinese college freshmen majoring in English from South China Normal University. Two participants were excluded from the analyses due to poor imaging quality, and three others because they did not take part in the second session. Thus, the final sample included 20 participants (mean age: 18.43 years, SD: 0.59), of which 18 participants were females. All participants were right-handed with normal or corrected-to-normal vision and no history of neurological disorders or traumatic brain injury. The Research Ethics Committee of South China Normal University approved this research. All participants signed written informed consent prior to participating in the experiment and received monetary compensation for their participation after completing the experiment.

This study consisted of two sessions: one during the first semester of university (i.e., Session 1) and another during the third semester (i.e., Session 2). Both sessions took place in October and November, with approximately one year in between the two sessions. Throughout this year, the participants took various English courses in an immersive English classroom setting. They had about 6–8 h of interactive English each weekday, suggesting an immersive L2 learning experience. In both sessions, all participants completed a language background questionnaire in which they rated their proficiency and percentage of language use for each language (see Table 1). The reported percentage of English use in daily life was 21.9% at Session 1 and 27.3% at Session 2. Language proficiency was assessed using both subjective and objective measures. For the subjective measure, participants assessed their language proficiency on a scale of 1–7 (1 = not proficient, 7 = very proficient). Further, a paired samples *t*-test indicated that the participants were unbalanced Chinese–English bilinguals with higher proficiency in Chinese than English ($p_s < 0.001$). For the objective measure, they completed the Oxford Placement Test (OPT, Geranpayeh, 2003) to assess their objective English proficiency in Session 2. Besides, participants reported an average AOA of 7.5 years (SD = 2.8, range:3–13) for English.

2.2. sMRI data acquisition

Structural images were collected on a 3 T Siemens Trio scanner equipped with a 12-channel phase array head coil at the MRI center of South China Normal University. T1-weighted MPRAGE images (TR =

1900 ms, TE = 2.52 ms, flip angle = 9°, FOV = 256 × 256 mm², matrix = 204 × 204, slice thickness = 1 mm, voxel size 1 × 1 × 1 mm³) were acquired from each participant in two sessions with approximately one year in between. The scan lasted 4 min and 26 s.

2.3. Preprocessing

The MPRAGE images were processed using the Computational Anatomy Toolbox (CAT12) (<http://www.neuro.uni-jena.de/cat/>), part of Statistical Parametric Mapping (SPM12) (<http://www.fil.ion.ucl.ac.uk/spm/software/spm12>), on the MATLAB R2013b platform (MathWorks, MA). The images were processed using a longitudinal processing stream as is advised for this longitudinal type of data. During preprocessing, the images were segmented into gray matter, white matter, and cerebral spinal fluid components. Then the data were normalized to MNI152 space using Diffeomorphic Anatomic Registration Through Exponentiated Lie algebra algorithm (DARTEL). Finally, the segmented GM images were smoothed with an 8 mm full width half maximum (FWHM) isotropic Gaussian kernel.

2.4. ROI-based analyses

To examine differences in regions implicated in bilingual language control processing during L2 learning ROI-based analyses of GMV were conducted. In the current study, we analyzed three GMV ROIs that play an important role in bilingual control according to the BAPSS model and DRM, namely the left ACC, right IFG, and LCN (see Fig. 1). We also included the left OCP as a control ROI because BAPSS model proposed that bilinguals rely more on this region with L2 learning. Mean GMV values for the four ROIs were extracted using the Neuromorphometrics atlas (<http://neuromorphometrics.com/>). Then paired-sample *t*-tests were applied to examine whether GMV changes occurred in these regions across L2 learning. The results were corrected for multiple comparisons using false-discovery rate correction (FDR correction). A ROI-analysis approach instead of a whole-brain analysis approach was chosen because we were especially interested in potential changes in brain structure associated with language control in the current study.

2.5. The relationship between GMV and language control performance

To assess whether the detected GMV changes were associated with

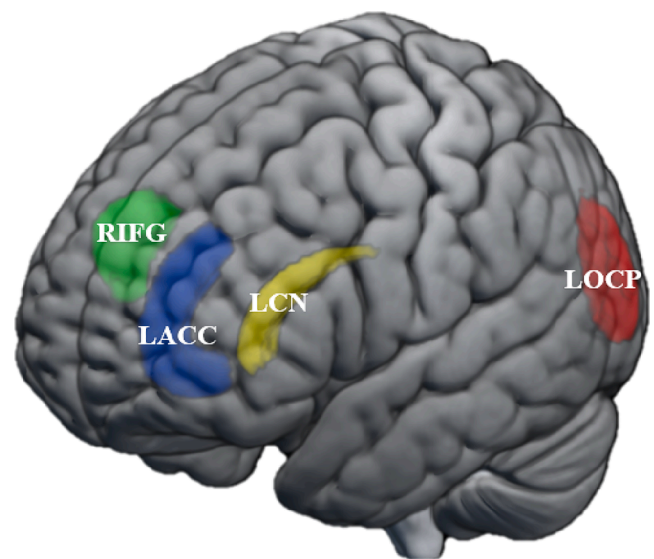


Fig. 1. Four ROIs for the ROI-based analyses. LACC = left anterior cingulate cortex, RIFG = right inferior frontal gyrus, LCN = left Caudate, LOCP = left occipital pole.

Table 1

The mean linguistic scores for participants with standard deviation in parentheses.

	Session 1	Session 2	<i>p</i> -value
Self-assessed proficiency score in Chinese	6.19 (0.91)	5.94 (0.65)	0.261
Self-assessed proficiency score in English	4.42 (0.70)	4.81 (0.57)	0.014
OPT score	–	41.10 (3.12)	–
Percentage of English use in daily life (%)	21.90 (15.52)	27.30 (10.79)	0.109

Note: *p*-values correspond to the paired samples *t*-tests between Session 1 and Session 2 and OPT is the objective measure of English proficiency.

their language control abilities, participants also performed a behavioral language switching task outside of the scanner in both Session 1 and Session 2. Language switching measures the ability to resolve the conflict between languages. For the language switching task, sixteen pictures were selected from the database of Zhang and Yang (2003), of which four were used during the practice stage. The twelve experimental pictures were matched on familiarity, visual complexity, and image agreement based on Chinese and English norm data from Snodgrass and Vanderwart (1980) and Zhang and Yang (2003). During the experiment, participants were first familiarized with the pictures and their corresponding names in both Chinese and English. This was done until participants could name all pictures correctly. Participants saw the pictures between 1 and 2 times. Afterward, they performed one practice session with 12 trials prior to the experimental language switching experiment. The language switching task included two blocks, each containing 48 switch trials and 48 non-switch trials, which were presented in a pseudo-randomized manner.

Each trial began with both a fixation cross and a Chinese or American flag for 500 ms. Next, a picture was presented for 1500 ms, while the fixation and flag stayed on the screen. Participants were instructed to name each picture in the language indicated by the Chinese or American flag as quickly and accurately as possible. The Chinese flag indicated that the picture had to be named in Chinese, while the American flag indicated it had to be named in English. Then a screen with a fixation was presented as a jittered inter-stimulus-interval (ISI) between 2000 ms and 5500 ms (in steps of 500 ms). The timing and order of trial presentation within each block were optimized for estimation efficiency using optseq2 (<http://surfer.nmr.mgh.harvard.edu/optseq/>).

In the language switching task, the switch cost has been understood to index a reactive type of **language control** that resolves interference from the non-target language in a trial-by-trial fashion and is calculated by subtracting performance in language repeat trials from language switch trials (Timmer, Calabria, & Costa, 2019; Timmer, Christoffels, & Costa, 2019; Liu, de Bruin, Jiao, Li, & Wang, 2021; Liu, Jiao, Li, Timmer,

& Wang, 2021; for a review see Bobb & Wodniecka, 2013). We conducted a paired-sample *t*-test to assess whether the language switch cost was influenced by one-year of L2 learning. Next, partial correlation analyses were conducted to assess the relationships between changes in GMV and changes in the switch cost measured as a difference in response times (RT), using age, gender, and L2 AOA as nuisance covariates.

2.6. The relationship between GMV and L2 Proficiency/L2 AOA in bilinguals

As recent studies recommended to model bilingualism/L2 learning as a gradient measure rather than an all-or-none phenomenon (DeLuca, Rothman, Bialystok, & Pliatsikas, 2019; Sulpizio, Del Maschio, Del Mauro, Fedeli, & Abutalebi, 2020), we provided additional insight to experience-based factors effects of bilingualism on the structural brain by correlating L2 AOA and L2 proficiency (i.e., OPT score) with GMV changes, controlling for age and gender.

3. Results

3.1. ROI-based results

As shown in Fig. 2 and Table 2, GMV in the right IFG ($p = 0.018$) and left ACC ($p = 0.042$) decreased from Session 1 to Session 2, although the

Table 2
GMV results for ROI analyses.

Region of interest	<i>t</i> -value	<i>p</i> -value	FDR corrected <i>p</i> -value
LACC	2.176	0.042	0.056
RIFG	2.589	0.018	0.046
LCN	0.306	0.763	0.779
LOCP	-2.467	0.023	0.046

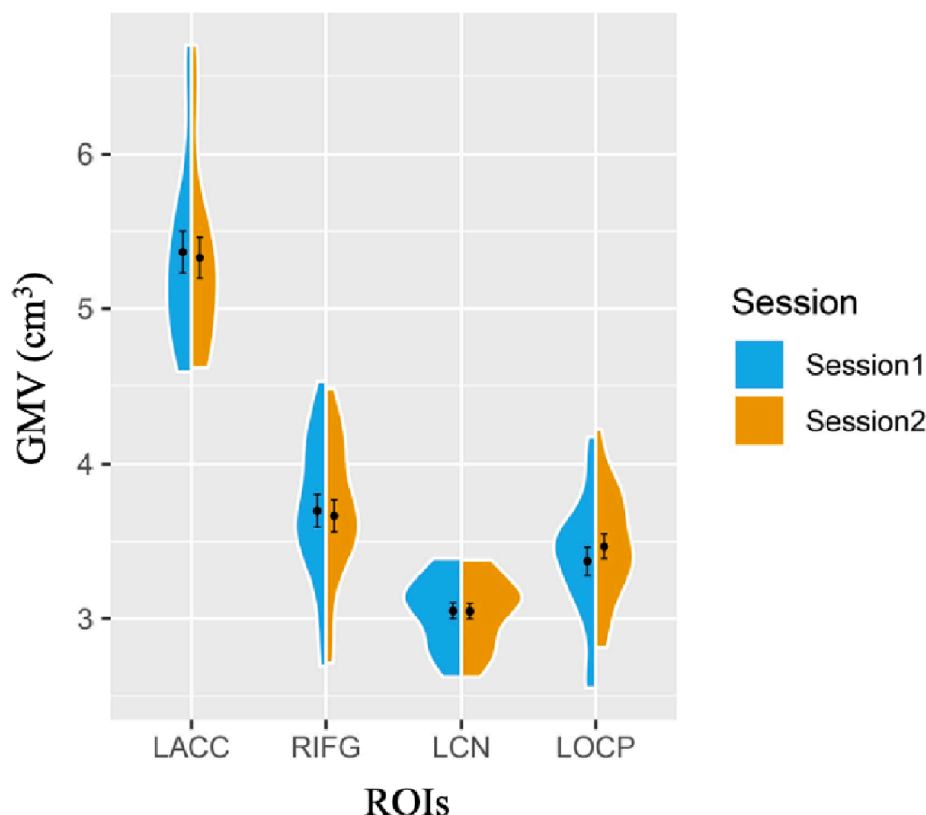


Fig. 2. Split violin plots for GMV in four ROIs separated for Session 1 and Session 2. Error bars represent Standard Errors (SE).

later finding was marginal after FDR correction. In contrast, GMV increased in the left OCP ($p = 0.023$) across the two Sessions, while GMV remained the same in the LCN ($p = 0.763$).

3.2. Results for the relationship between GMV and language control performance

Participants' performance on the language switch task revealed that the switch cost decreased by 20 ms ($t = 2.953$, $p = 0.008$) from Session 1 (31 ms) to Session 2 (11 ms). Critically, the partial correlation analysis showed that the decrease in the language switch cost was significantly correlated with the decrease of GMV in the left ACC ($r = 0.615$, 95% CI = [0.237, 0.831], $p = 0.015$, FDR-corrected $p = 0.030$) and of the right IFG ($r = 0.695$, 95% CI = [0.365, 0.870], $p = 0.004$, FDR-corrected $p = 0.016$) (see Fig. 3). However, no significant correlations were observed between the decrease in the language switch cost and the increase of GMV in the left OCP ($r = 0.088$, 95% CI = [-0.369, 0.511], $p = 0.756$, FDR-corrected $p = 0.756$).

3.3. Results for the relationship between GMV and L2 Proficiency/L2 AOA in bilinguals

As shown in Fig. 4, OPT score was significantly correlated with the decrease of GMV in the right IFG ($r = -0.614$, 95% CI = [-0.831, -0.235], $p = 0.007$, FDR-corrected $p = 0.028$). No significant correlation was detected between the OPT score and the decrease of GMV in the left ACC or the left OCP (p s > 0.05).

L2 AOA was significantly correlated with the decrease of GMV in the left ACC ($r = 0.595$, 95% CI = [0.207, 0.821], $p = 0.009$, FDR-corrected $p = 0.036$). No significant correlation was detected between L2 AOA and the decrease of GMV in the right IFG or the left OCP (p s > 0.05).

4. Discussion

The present study investigated how grey matter structure, related to language control, adapt to long-term classroom L2 learning. Chinese College freshmen majoring in English underwent sMRI scanning twice across one year of L2 learning. VBM analyses showed decreased GMV in the left ACC and the right IFG from Session 1 to Session 2. The decreases in both regions positively correlated with the decrease in the behavioral language switch cost, an index of bilingual language control. These findings indicate that classroom L2 learning induced anatomical changes in brain regions that are implicated in bilingual language control. Moreover, our experience-based factors of L2 AoA and L2 proficiency distinguished between the role of the right IFG and the left ACC. While the left ACC positively correlated with individual L2 AoA, the right IFG negatively correlated with individual L2 proficiency. Thus, the mechanism of bilingual language control plays a crucial role in structural brain adaptations due to classroom L2 learning. These structural brain adaptations reveal individual variability depending on L2 AoA and L2 proficiency.

4.1. L2 learning induces structural adaptations of brain regions associated with language control

The main finding in the current study was that GMV in both the left ACC and the right IFG, two frontal regions involved in language control, significantly decreased with classroom L2 learning. Critically, these changes of GMV in both frontal regions significantly correlated with behavioral changes in language control (i.e., as measured in the switch cost). These findings reveal a switch away from cortico-frontal regions to subcortical and posterior regions with prolonged L2 learning as also proposed in the BAPSS (Grundy et al., 2017) and DRM (Pliatsikas, 2020)

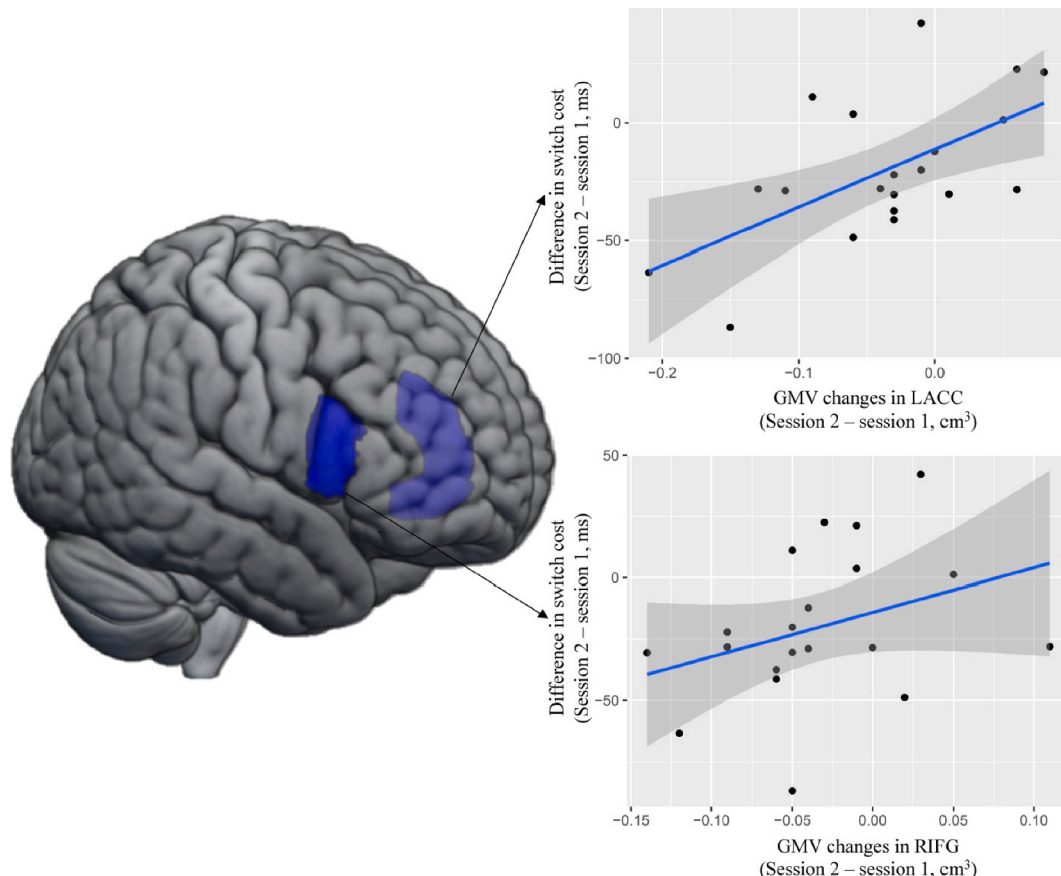


Fig. 3. Correlation of changes from Session 1 to Session 2 between both gray matter volume (GMV) in left ACC/right IFG and language switch costs.

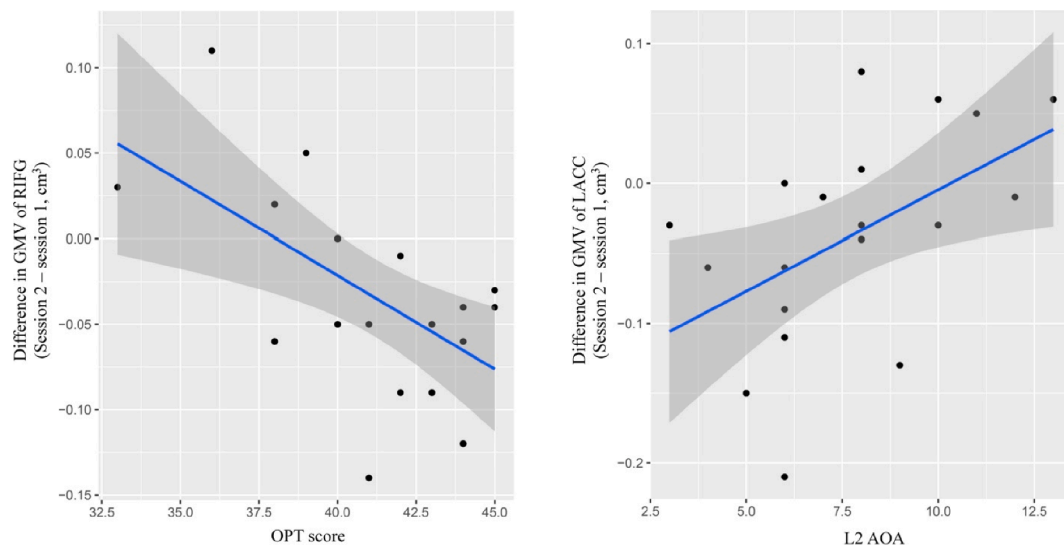


Fig. 4. In the left panel, the negative correlation shows that the higher the OPT score, the greater the decrease of GMV in the right IFG after L2 learning (FDR corrected $p < 0.05$). In the right panel, the positive correlation shows that the earlier the age of acquisition, the greater the decrease in GMV in the left ACC after L2 learning (FDR corrected $p < 0.05$).

frameworks. While most previous studies showed an increase of GMV in frontal regions with increased L2 learning and degree of bilingualism (for a review, see Li et al., 2014), we revealed a decrease in GMV in frontal regions. This reason for this could be that participants in the current study moved from the *consolidation* stage during the first Session to the *peak efficiency* stage during the second Session a year later as proposed in the DRM framework, while previous studies moved from *initial exposure* stage to the *consolidation* stage. This is in line with GMV increases during the *initial exposure* stage of L2 learning, due to novel demands of bilingual control, found in other studies (see Li et al., 2014), and decreases of GMV during the later *consolidation* and *peak efficiency* stages of L2 learning, due to more automatized and efficient language control with extensive exposure to L2, in the present study. Together with the decreased need for frontal regions, we saw an increased demand for GMV in the left OCP as proposed in the BAPPS framework. The occipital regions are mainly responsible for perceptual/motor functions (Grundy et al., 2017) and therefore we did not observe correlations between the left OCP and the behavioral language control measure. To conclude, structural brain adaptations in the frontal region provided evidence that bilingual language control plays a crucial role during classroom L2 learning.

Notably, GMV in the LCN remained the same across one year of classroom L2 learning. The lack of adaptations in this area was also reported in another recent study, which examined structural brain changes in cognitive control networks for native English speakers across approximately four months of L2 Spanish classroom learning (Legault et al., 2019). However, Deluca et al. (2019) observed decreases of GMV in the LCN due to immersion in an L2 environment across three years. The crucial difference between the former studies (the present and Legault et al., 2019) and Deluca et al. (2019) is the language environment the participants are residing in. While the participants in Legault et al. (2019) and our study were mainly residing in their native country and learning an L2 in the classroom setting, Deluca et al. (2019) participants were residing in their non-native country and experienced intensive L2 immersion. Notably, students' L2 experience differs between learning in the classroom or an immersive, naturalistic environment (e.g., immigrants). For example, L2 classroom learning aims to improve L2 proficiency with constant feedback from instructors on L2 proficiency. This experience is lacking in naturalistic immersed L2 environments. We, therefore, argue that the type of L2 experience may be distinguished in the LCN region: the lack of adaptations in the LCN in the present study compared to modulations found by Deluca et al. (2019)

may arise from the difference in L2 learning experience. It also should be noted that Deluca et al. (2019) used a vertex analysis to examine local shape changes in the subcortical structure, while Legault et al. (2019) and the present study examined volume for the whole structure. The whole structure analysis might not have been sufficiently granular to detect changes in the subcortical structure.

4.2. The relationships between structural brain adaptations and individual differences in L2 learning experience

Two experience-based factors of L2 learning, namely L2 AoA and L2 proficiency, revealed differential associations with structural brain changes. For AoA, we found that participants who learned their L2 at an earlier age showed a greater decrease of GMV in the left ACC as compared to participants who learned their L2 at a later stage. This finding is consistent with previous studies purporting a significant relationship between L2 AoA and brain structure density changes, such as of GMV (Mechelli et al., 2004) and white matter integrity (DeLuca, Rothman, Bialystok, & Pliatsikas, 2019; Luk, Mesite, & Leon Guerrero, 2020). While most previous studies examined L2 AoA in cross-sectional data, our study revealed the effect of L2 AoA in a longitudinal design. This longitudinal design demonstrated the direct relationship between L2 AoA and the left ACC. As GMV changes in the left ACC significantly correlated with both behavioral changes in language control and the L2 AoA, it could be that L2 AoA is actually a moderator of the other correlation (i.e., GMV with behavioral language control). However, the regression analysis indicated no such potential moderating effect ($\beta = -0.169$, $t = -0.899$, $p = 0.386$).

For L2 proficiency, participants with higher L2 proficiency (as measured by OPT scores) showed a greater decrease of GMV in the right IFG after L2 learning than participants with lower L2 proficiency. This is in line with previous studies that have indicated a relationship between L2 proficiency and this brain structure (Del Maschio et al., 2018; Hosoda, Tanaka, Nariyai, Honda, & Hanakawa, 2013). However, it should be noted that our finding is different from that in Hosoda et al. (2013), which revealed that bilinguals with higher L2 proficiency (as measured by TOEIC scores) showed an increase, instead of our decrease, of GMV in the right IFG. A possible explanation for this difference is that the participants in both studies were at different stages of L2 learning. Specifically, the participants in Hosoda et al. (2013) might be at the initial stage of L2 learning, while the participants in our study were at the later *consolidation* or *peak efficiency* stages of L2 learning. This would

be in line with the predictions of the DRM framework that the GMV in the right IFG should increase at an early stage and decrease at a late stage with L2 learning (Pliatsikas, 2020). Thus, differential changes in GMV in the right IFG are observed depending on the stage of L2 language learning.

Taken together, the observed correlations between structural brain adaptations and individual L2 learning experience (i.e., L2 AoA and L2 proficiency) provide us a broader insight into the relationship between language experience factors and brain adaptations induced during L2 learning.

4.3. Limitations and future directions

One limitation of our sMRI study was that we did not include a control group. It might be argued that the observed changes in brain structure and the reduction in the behavioral switch cost arise from the training/repetition effect that have previously been reported (Kang et al., 2017; Kang, Ma, & Guo, 2018; Timmer et al., 2019; Wu, Kang, Ma, Gao, & Guo, 2018) instead of arising from L2 learning as we suggested in the present study. To exclude this possibility, we introduced a behavioral control group with 25 college freshmen (22 females, mean age: 19.32 years) not majoring in foreign language programs. They were asked to complete the language switching task twice, approximately one month apart. The results revealed a similar language switch cost in both testing sessions (12 ms vs. 9 ms, $t = -0.54$, $p > 0.05$). While previously observed decreases in the switch cost (e.g., Kang et al., 2017) were shorter term than the two months in the control experiment and one year in our experimental study we believe we can assume that increases in bilingual language control are not due to task repetition. Therefore, we suggest the origin of the correlation between brain changes and behavioral changes in language switch cost is specifically related to L2 learning.

Another limitation was that the sample size of 20 is relatively small. Future studies should recruit larger sample sizes. Further, the present study investigated an adult population that learned the L2 at a specific time point during young adulthood. Therefore, the present results cannot be generalized to all populations or different stages of L2 learning. Future studies should recruit participants of varying ages (i.e., from children to aging people) and at different stages of L2 learning to increase our understanding of the complexity of bilingual language experience. Future studies could also examine more detailed aspects of L2 learning experiences that can provide further understanding of the different findings in the bilingualism literature. This could further advance the full picture of structural brain adaptations as a function of L2 learning.

5. Conclusion

The current study examined GMV changes, typically found in language control networks, across one year of classroom L2 learning. Our findings suggest that L2 learning may lead to decreases of GMV in the left ACC and the right IFG. These are two key brain regions involved in language control processing that have been implicated in previous literature (for a review, see DeLuca et al., 2020). Critically, the observed changes in both regions were correlated with participants' behavioral performance on bilingual language control (i.e., switch cost). Further, the observed structural changes vary with individual differences in L2 learning experiences, specifically L2 AoA and L2 proficiency. Taken together, these findings indicate the dynamic nature of structural brain adaptations as a function of classroom L2 learning and enrich our understanding of the mechanism underlying such adaptations.

Statement of significance

This study advances our understanding of structural brain adaptations due to L2 learning. We revealed changes in differential experience-

dependent mechanisms by correlating brain adaptations with individual difference in L2 learning. While L2 AoA is associated with decreases in the left ACC and L2 proficiency with decreases in the right IFG, both regions are involved in bilingual language control mechanism that we show plays a crucial role during L2 learning. This provides convergent support for the proposal of dynamic brain adaptations throughout the learning process of a second language.

CRedit authorship contribution statement

Cong Liu: Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Lu Jiao:** Conceptualization, Investigation, Writing – review & editing. **Kalinka Timmer:** Writing – review & editing. **Ruiming Wang:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

We thank Vincent DeLuca for his helpful comments in the earlier version of this manuscript.

Funding

This research was supported by the Natural Science Foundation of Guangdong Province (2020A1515010521), Qingdao Philosophy and Social Sciences Planning Funding (QDSKL2001098), and National Natural Science Foundation of China (62107024). Kalinka Timmer was supported by postdoctoral funding from Narodowa Agencja Wymiany Akademickiej in Poland with the Ulam grant (PPN/ULM/2019/1/00215).

References

- Bak, T. H., Long, M. R., Vega-Mendoza, M., Sorace, A., & Allen, P. (2016). Novelty, challenge, and practice: The impact of intensive language learning on attentional functions. *PLoS one*, *11*(4), e0153485.
- Bialystok, E. (2017). The bilingual adaptation: How minds accommodate experience. *Psychological Bulletin*, *143*(3), 233–262.
- Bobb, S. C., & Wodniecka, Z. (2013). Language switching in picture naming: What asymmetric switch costs (do not) tell us about inhibition in bilingual speech planning. *Journal of Cognitive Psychology*, *25*(5), 568–585.
- Danylkiv, A., & Krafnick, A. J. (2020). A meta-analysis of gray matter differences between bilinguals and monolinguals. *Frontiers in Human Neuroscience*, *14*, 146.
- De Bruin, A. (2019). Not all bilinguals are the same: A call for more detailed assessments and descriptions of bilingual experiences. *Behavioral Sciences*, *9*(3), 33.
- Del Maschio, N., Fedeli, D., Sulpizio, S., & Abutalebi, J. (2019). The relationship between bilingual experience and gyrfication in adulthood: A cross-sectional surface-based morphometry study. *Brain and Language*, *198*, 104680. <https://doi.org/10.1016/j.bandl.2019.104680>.
- Del Maschio, N., Sulpizio, S., Gallo, F., Fedeli, D., Weekes, B. S., & Abutalebi, J. (2018). Neuroplasticity across the lifespan and aging effects in bilinguals and monolinguals. *Brain and Cognition*, *125*, 118–126.
- DeLuca, V. (2019). Future directions in examining neurological adaptation to bilingual experiences, 117906951987659 *Journal of Experimental Neuroscience*, *13*. <https://doi.org/10.1177/1179069519876597>.
- DeLuca, V., Rothman, J., Bialystok, E., & Pliatsikas, C. (2019). Redefining bilingualism as a spectrum of experiences that differentially affects brain structure and function. *Proceedings of the National Academy of Sciences*, *116*(15), 7565–7574.
- DeLuca, V., Rothman, J., & Pliatsikas, C. (2019). Linguistic immersion and structural effects on the bilingual brain: A longitudinal study. *Bilingualism: Language and Cognition*, *22*(5), 1160–1175.
- DeLuca, V., Segaert, K., Mazaheri, A., & Krott, A. (2020). Understanding bilingual brain function and structure changes? U Bet! A Unified Bilingual Experience Trajectory model. *Journal of Neurolinguistics*, *56*, 100930. <https://doi.org/10.1016/j.jneuroling.2020.100930>.

- Dijkstra, T., & van Heuven, W. J. B. (2002). The architecture of the bilingual word recognition system: From identification to decision. *Bilingualism: Language and Cognition*, 5(3), 175–197.
- Draganski, B., Gaser, C., Busch, V., Schuierer, G., Bogdahn, U., & May, A. (2004). Changes in grey matter induced by training. *Nature*, 427(6972), 311–312.
- Draganski, B., & May, A. (2008). Training-induced structural changes in the adult human brain. *Behavioural Brain Research*, 192(1), 137–142.
- Fedeli, D., Del Maschio, N., Sulpizio, S., Rothman, J., & Abutalebi, J. (2021). The bilingual structural connectome: Dual-language experiential factors modulate distinct cerebral networks. *Brain and Language*, 220, 104978. <https://doi.org/10.1016/j.bandl.2021.104978>.
- García-Pentón, L., Fernández García, Y., Costello, B., Duñabeitia, J. A., & Carreiras, M. (2016). The neuroanatomy of bilingualism: How to turn a hazy view into the full picture. *Language, Cognition and Neuroscience*, 31(3), 303–327.
- Geranpayeh, A. (2003). A quick review of the English Quick Placement Test. *Research Notes*, 12(3), 8–10.
- Green, David W. (1998). Mental control of the bilingual lexico-semantic system. *Bilingualism: Language and Cognition*, 1(2), 67–81.
- Grundy, J. G., Anderson, J. A. E., & Bialystok, E. (2017). Neural correlates of cognitive processing in monolinguals and bilinguals. *Annals of the New York Academy of Sciences*, 1396(1), 183–201.
- Hervais-Adelman, Alexis, Egorova, Natalia, & Golestani, Narly (2018). Beyond bilingualism: Multilingual experience correlates with caudate volume. *Brain Structure and Function*, 223(7), 3495–3502.
- Hosoda, C., Tanaka, K., Nariyai, T., Honda, M., & Hanakawa, T. (2013). Dynamic neural network reorganization associated with second language vocabulary acquisition: A multimodal imaging study. *Journal of Neuroscience*, 33(34), 13663–13672.
- Ilg, R., Wohlschläger, A. M., Gaser, C., Liebau, Y., Dauner, R., Woller, A., ... Muhlau, M. (2008). Gray matter increase induced by practice correlates with task-specific activation: A combined functional and morphometric magnetic resonance imaging study. *Journal of Neuroscience*, 28(16), 4210–4215.
- Jiao, L., Liu, C., Schwieter, J. W., & Chen, B. (2021). Switching between newly learned languages impacts executive control. *Psychophysiology*, 58(10), e13888.
- Kang, C., Fu, Y., Wu, J., Ma, F., Lu, C., & Guo, T. (2017). Short-term language switching training tunes the neural correlates of cognitive control in bilingual language production. *Human Brain Mapping*, 38(12), 5859–5870.
- Kang, C., Ma, F., & Guo, T. (2018). The plasticity of lexical selection mechanism in word production: ERP evidence from short-term language switching training in unbalanced Chinese-English bilinguals. *Bilingualism: Language and Cognition*, 21(2), 296–313.
- Klein, D., Mok, K., Chen, J.-K., & Watkins, K. E. (2014). Age of language learning shapes brain structure: a cortical thickness study of bilingual and monolingual individuals. *Brain and Language*, 131, 20–24.
- Krafnick, A. J., Flowers, D. L., Napoliello, E. M., & Eden, G. F. (2011). Gray matter volume changes following reading intervention in dyslexic children. *Neuroimage*, 57(3), 733–741.
- Kraus, N., & White-Schwoch, T. (2017). Neurobiology of everyday communication: What have we learned from music? *The Neuroscientist*, 23(3), 287–298.
- Legault, J., Fang, S.-Y., Lan, Y.-J., & Li, P. (2019). Structural brain changes as a function of second language vocabulary training: Effects of learning context. *Brain and Cognition*, 134, 90–102.
- Li, P., Legault, J., & Litcofsky, K. A. (2014). Neuroplasticity as a function of second language learning: Anatomical changes in the human brain. *Cortex*, 58, 301–324.
- Liu, C., de Bruin, A., Jiao, L., Li, Z., & Wang, R. (2021). Second language learning tunes the language control network: A longitudinal fMRI study. *Language, Cognition and Neuroscience*, 36(4), 462–473.
- Liu, C., Jiao, L., Li, Z., Timmer, K., & Wang, R. (2021). Language control network adapts to second language learning: A longitudinal rs-fMRI study. *Neuropsychologia*, 150, 107688. <https://doi.org/10.1016/j.neuropsychologia.2020.107688>.
- Luk, G., Mesite, L., & Leon Guerrero, S. (2020). Onset age of second language acquisition and fractional anisotropy variation in multilingual young adults. *Journal of Neurolinguistics*, 56, 100937. <https://doi.org/10.1016/j.jneuroling.2020.100937>.
- Luo, D., Kwok, V. P. Y., Liu, Q., Li, W., Yang, Y., Zhou, K., ... Tan, L. H. (2019). Microstructural plasticity in the bilingual brain. *Brain and Language*, 196, 104654. <https://doi.org/10.1016/j.bandl.2019.104654>.
- Maguire, E. A., Gadian, D. G., Johnsrude, I. S., Good, C. D., Ashburner, J., Frackowiak, R. S. J., & Frith, C. D. (2000). Navigation-related structural change in the hippocampi of taxi drivers. *Proceedings of the National Academy of Sciences*, 97(8), 4398–4403.
- Mårtensson, J., Eriksson, J., Bodammer, N. C., Lindgren, M., Johansson, M., Nyberg, L., & Lövdén, M. (2012). Growth of language-related brain areas after foreign language learning. *NeuroImage*, 63(1), 240–244.
- Mechelli, A., Crinion, J. T., Noppeney, U., O'Doherty, J., Ashburner, J., Frackowiak, R. S., & Price, C. J. (2004). Structural plasticity in the bilingual brain. *Nature*, 431, 757.
- Paap, K. R., Johnson, H. A., & Sawi, O. (2015). Bilingual advantages in executive functioning either do not exist or are restricted to very specific and undetermined circumstances. *Cortex*, 69, 265–278.
- Pliatsikas, C. (2020). Understanding structural plasticity in the bilingual brain: The Dynamic Restructuring Model. *Bilingualism: Language and Cognition*, 23(2), 459–471.
- Pliatsikas, C., DeLuca, V., Moschopoulou, E., & Saddy, J. D. (2017). Immersive bilingualism reshapes the core of the brain. *Brain Structure and Function*, 222(4), 1785–1795.
- Pliatsikas, C., DeLuca, V., & Voits, T. (2020). The many shades of Bilingualism: Language experiences modulate adaptations in brain structure. *Language Learning*, 70(S2), 133–149.
- Snodgrass, J. G., & Vanderwart, M. (1980). A standardized set of 260 pictures: Norms for name agreement, image agreement, familiarity, and visual complexity. *Journal of Experimental Psychology: Human Learning and Memory*, 6(2), 174–215.
- Sulpizio, S., Del Maschio, N., Del Mauro, G., Fedeli, D., & Abutalebi, J. (2020). Bilingualism as a gradient measure modulates functional connectivity of language and control networks. *NeuroImage*, 205, 116306. <https://doi.org/10.1016/j.neuroimage.2019.116306>.
- Timmer, K., Calabria, M., & Costa, A. (2019). Non-linguistic effects of language switching training. *Cognition*, 182, 14–24.
- Timmer, K., Christoffels, I. K., & Costa, A. (2019). On the flexibility of bilingual language control: The effect of language context. *Bilingualism: Language and Cognition*, 22(3), 555–568.
- Wu, J., Kang, C., Ma, F., Gao, X., & Guo, T. (2018). The influence of short-term language-switching training on the plasticity of the cognitive control mechanism in bilingual word production. *Quarterly Journal of Experimental Psychology*, 71(10), 2115–2128.
- Yamasaki, B. L., Stocco, A., Liu, A. S., & Prat, C. S. (2019). Effects of bilingual language experience on basal ganglia computations: A dynamic causal modeling test of the conditional routing model. *Brain and Language*, 197, Article 104665.
- Zhang, Q., & Yang, Y. (2003). The deferminers of picture-naming latency. *Acta Psychologica Sinica*, 35, 447–454.
- Zou, L., Ding, G., Abutalebi, J., Shu, H., & Peng, D. (2012). Structural plasticity of the left caudate in bimodal bilinguals. *Cortex*, 48(9), 1197–1206.